EVIDENCE OF A SECONDARY STREAM OF NEUTRAL FLUXES AT 1 AU

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ABSTRACT

Neutral atom and solar wind plasma wave data sets are presented and interpreted as evidence of the neutral atom environment at 1 AU. These data suggest the presence of a secondary stream of neutrals at 1 AU between 262° and 292° ecliptic longitude. These directions are 10°-40° from the nominal upstream direction at 252° ecliptic longitude which results from the motion of the Sun relative to the local interstellar cloud (LIC), but consistent with the Apex of the Sun's Way at 271° ecliptic longitude which is defined by the motion of the Sun relative to nearby stars and with the Galactic center at 267° ecliptic longitude. One possible explanation is that there is a previously unrecognized secondary stream of hot neutrals entering the heliosphere from that direction, perhaps due to nearby hot gas between our local cloud and the G cloud or due to an asymmetry in the heliosphere induced by a tilted interstellar magnetic field.

Introduction

The Sun moves relative to the local interstellar cloud at about 25 km/s in a direction that places the Earth upstream of the Sun in the interstellar flow in early June of each year, about June 3 (day 154) when the Earth is at 252° ecliptic longitude [Witte et al., 1993; Gloeckler and Geiss, 2001; Lallement, 1996; Frisch, 2000]. The presence of this well-established stream leads to the natural expectation that neutral atom fluxes observed at 1 AU would be centered around the 72°/252° ecliptic longitude axis. However, a number of neutral atom data sets at 1 AU are not centered with this axis, but with larger ecliptic longitudes by 10°-40° depending on the data set in question.

Interstellar Neutral (ISN) Observations

Fuselier predicted prior to the IMAGE launch in March of 2000, based in part on earlier unpublished work by Gruntman, that the Low Energy Neutral Atom (LENA) Imager which responds to neutral atoms down to as low as about 10 eV [Moore et al., 2000] would be able to directly observe interstellar neutral atoms.

Although the direction from which the neutrals come is nominally outside of LENA's field-of-view, the trajectories of the heavy atoms, notably helium, are bent by the Sun's gravity into LENA's field-of-view. Additionally, when this occurs, the neutral atom velocities and that of the Earth are approximately anti-parallel, increasing their apparent energy beyond that gained simply by falling into the Sun's gravitational well. Fuselier predicted that the interstellar neutrals would be observed early in the calendar year and in the Winter of 2000/2001, LENA observed the predicted signal.

Figure 1 shows an example of this signal in spectrogram format with time on the x-axis, spacecraft spin on the y-axis, and the color indicating the count rate. The most intense signal is solar wind neutrals. Earth neutrals come from the direction of the Earth, indicated by the white lines around zero degrees, and the interstellar neutral signal appears in about the Earth ram direction.

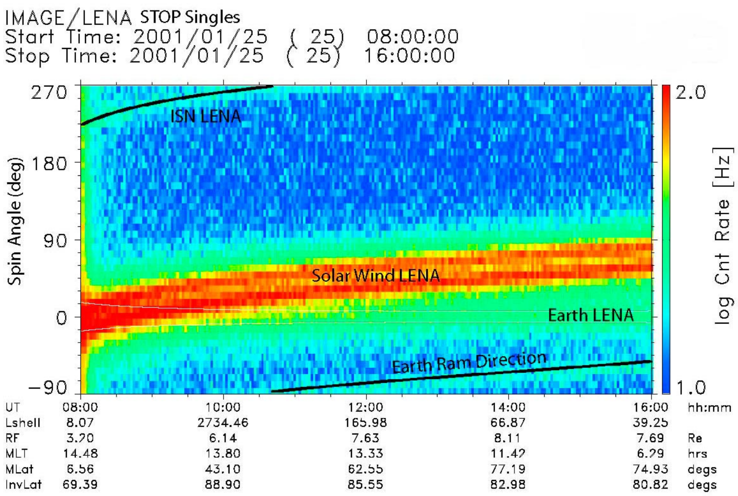


Fig. 1. LENA spectrogram showing ISN signal.

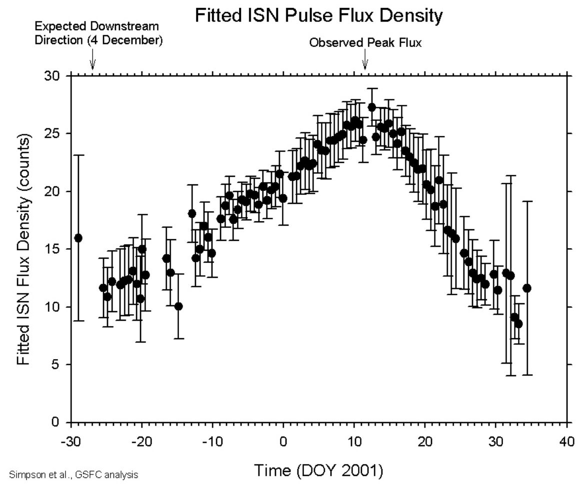


Fig. 2. ISN count rate versus day of year.

Because heavy atoms are focused in the downstream direction by solar gravity, the peak interstellar neutral flux is expected when the Earth is directly downstream, on December 4. To determine when the peak rate occurred, two groups on the LENA team independently used different techniques to extract the relatively weak signal and follow its rate versus time. The two groups reached the same conclusion, namely that the peak flux of interstellar neutrals occurred about forty days later than December 4, in early January. The results from one of the groups, the GSFC group, are shown in Figure 2. Attempts to get the peak location to agree better with the expected downstream direction by modeling the neutral helium velocity, taking into account the spacecraft motion, and incorporating instrument efficiencies were only able to shift the peak about seven days earlier in the year. So, there appears to be an unexplained shift of about thirty degrees in the peak rate of the directly observed interstellar neutrals.

These neutrals are deflected by the Sun's gravity and LENA responds to all species of neutrals over a wide energy range, so this signal is likely heavy atoms, but not necessarily low energy helium. Consequently, these results are not necessarily from the same population of neutrals observed by the Ulysses Neutral GAS experiment [Witte, 1992], which is optimized for low energy helium.

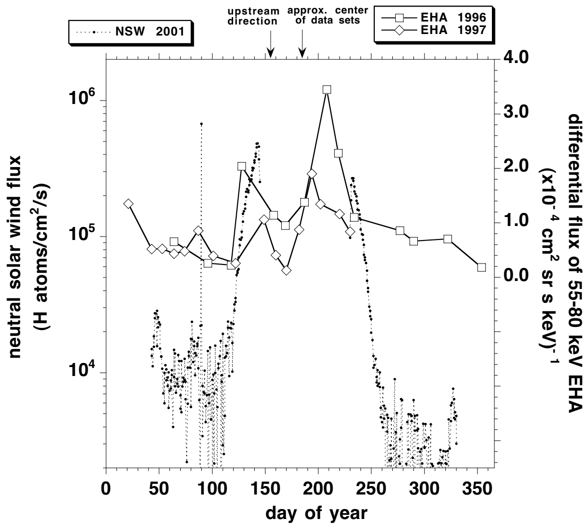
Neutral Solar Wind (NSW) Observations

The solar wind has a neutral component which forms when solar wind ions exchange charge with neutral atoms between the Sun and the Earth [Collier et al., 2001]. Although there are three potential sources for neutrals for solar wind charge exchange, interstellar neutrals, dust and the Earth's hydrogen geocorona [Collier et al., 2002], only one of these, interstellar neutrals, is expected have an annual periodicity due to the Earth's motion around the Sun [Bzowski et al., 1996].

The primary neutral for charge exchange with the solar wind, however, is expected to be interstellar hydrogen, primarily because hydrogen has a higher density and will charge exchange more readily with protons than neutral helium will [Gruntman, 1994]. Additionally, unlike helium, the hydrogen is relatively unaffected by solar gravity, being partially if not entirely balanced by radiation pressure, so that the highest hydrogen densities are found in the upstream, rather than downstream, region. Figure 6 of Bzowski et al. (1996) shows a model prediction for the annual variation of the neutral solar wind flux at 1 AU over a solar cycle. The predicted variation is between one and three orders of magnitude in the upstream direction with a peak flux close to 10^4 atoms/cm^2/s.

Figure 3 shows the annual variation of the neutral solar wind flux observed by LENA over the year 2001 (dashed line). Although the Sun, and hence the solar wind, is outside of LENA's field-of-view when the Earth is upstream of the Sun, there is evidence for an upwind enhancement of a couple orders of magnitude. However, when the peak center is inferred from the rise and fall, its location is estimated to be on day 184, about thirty days or thirty degrees later than expected based on the nominal upstream direction.

There are four major reasons why this upstream enhancement is not consistent with being due to light



From: Hilchenbach et al., Ap. J., 503:916-922, 1998 Aug 20, Fig. 6

Fig. 3. EHA data from HSTOF on SOHO.

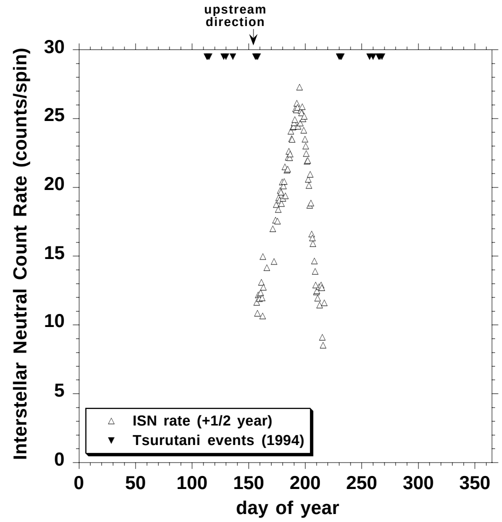


Fig. 4. Tsurutani waves and ISN data.

contamination: (i) Such an effect should be symmetric with respect to the instrument's polar viewing and does not appear on the other side of LENA's field-of-view. (ii) Such a signal was not present during calibration when tests with a UV source of 10 solar units showed a response that increased as the aperture was directed toward the source, not the opposite as would be required to explain the enhancement. (iii) The data shown in Fig. 3 are from only the proton peak of the time-of-flight (tof) spectrum. Light entering the tof unit gives a broad response over all tofs and does not result in a background-corrected enhancement in the proton peak. (iv) The increase in the hydrogen signal in the upstream direction is not accompanied by an associated increase in the background count rate determined from the tof spectrum, which would be expected if the signal were due to light.

The neutral solar wind flux is significantly higher than expected, with extrapolation of the observed flux suggesting that, at its peak, close to 1% of the solar wind density may be neutral (although the highest flux we measure is $\sim$0.2%). The flux is based on the assumption that the observed hydrogen has an energy of 1 keV. Although this does correspond roughly to the energy of the average solar wind velocity, the average solar wind energy will be higher and LENA's efficiency may be higher at the higher energies. Considering this and uncertainties in calibration, the observed neutral solar wind flux could be lower than shown in Fig. 3 by about a factor of four. It is also possible, as will be addressed in the next section, that LENA is responding to an enhanced flux of higher energy neutrals coming from the downwind direction, which would increase the apparent neutral solar wind flux.

Energetic Hydrogen Atom Observations

Figure 3 also shows energetic hydrogen atom data (solid line) from the High Energy Suprathermal Time-of-Flight (HSTOF) sensor on SOHO published by Hilchenbach et al. [1998] (data from their Fig. 6a). They examined quiet day fluxes of hydrogen atoms with energies between 55 and 80 keV and interpret these fluxes as coming from the heliosheath. Kóta et al. [2001] have argued that the HSTOF ENA observations are also consistent with an energetic ion population source accelerated at CIRs in the inner heliosphere.

Like the LENA neutral solar wind observations, HSTOF is looking back towards the Sun and, like LENA, HSTOF sees an enhancement in energetic neutrals between about day 120 and 250. However, unlike LENA, HSTOF is not looking directly back at the Sun, but 37° off the Sun-Earth line, so it is surprising that the enhancement occurs at about the same place. However, even when the data are plotted as a function of the actual ecliptic longitude HSTOF observes (see Hilchenbach et al., Fig. 6b), there is still a substantial shift, by about 15°, between the peak flux and the nominal upstream/downstream axis.

The enhancement is most pronounced in the anti-apex or heliotail direction because of two effects. First, in the heliotail direction the plasma flows outward so convection and diffusion operate in the same direction. Second, a spatial asymmetry will occur because the heliopause functions as a free escape boundary and is farther from the termination shock toward the heliotail than toward the nose. These conclusions appear to be independent of model details [Czechowski et al., 2001]. This shift is apparent in the HSTOF long term trending data shown in Figure 18 of Czechowski et al. [2001] as well. Note, however, that the fluxes HSTOF observes are higher by an order of magnitude than can be accounted for by the models they consider. Certainly an additional source of neutral gas, such as might be supplied by a secondary stream, would bring model and observations into closer agreement.

Wave Observations

Tsurutani et al. [1994] reported low frequency waves with periods near the proton gyroperiod at 1 AU observed by the magnetometer on ISEE-3. The events are unusual because the interplanetary magnetic field power spectrum at 1 AU is typically quite featureless, exhibiting a relatively smooth Kolmogorov $\nu^{-5/3}$ dependence. However, during these events (see their Fig. 3), Tsurutani et al. saw broad increases in the wave power near the proton cyclotron frequency, atypical in the normal solar wind.

Tsurutani et al. considered pickup of cold hydrogen neutrals as the most likely source of the waves and list interstellar neutrals as a possible candidate. The dates of their events are distributed over a three year period from 1978-1981 (see their Table 1). However, the day of year of these events falls into two clusters, as shown at the top of Figure 4, which appear to be centered not with the upstream direction, but about thirty degrees later.

In the event these wave observations are associated with elevated neutral fluxes centered at an ecliptic longitude somewhere between 262° and 292°, then a natural question is why would this wave activity only occur in the regions of the neutral atom gradients. One possible explanation is that it results from Earth crossings of the parabolic exclusion boundary [Holzer, 1977]. For values of the ratio of the radiation to gravitational force $\mu > 1$, hydrogen is unable to penetrate to the Sun and the fobidden region forms a parabolic boundary, which, in analogy to the magnetosheath, has an associated hydrogen sheath of substantially increased density. For a static boundary and reasonable values of μ, the Earth will traverse this sheath twice annually in the upstream direction (see Holzer, 1977, Fig. 4b). However, the boundary is likely irregular and in near constant motion, causing multiple traversals and bursty activity during the appropriate times of year, as observed in Tsurutani et al.'s events. In fact, examining Tsurutani et al.'s wave events, they do resemble, in the sense of having multiple closely-spaced events, the traversals of boundaries such as the magnetopause and bow shock.

Discussion and Conclusions

Figure 5 shows all four of the data sets discussed in this paper on a single plot. The data have a symmetry point substantially later than expected based on the nominal upstream direction but appear to be consistent with a direction very close to the solar apex at 271°, which is the Sun's apparent motion relative to the nearby stars, and the Galactic center at 267°. One possibility is that this may be due to a secondary stream of neutrals which enters the heliosphere at an ecliptic longitude somewhere between 262° and 292°. The wave data and the downstream directly observed neutral data suggest a lower energy component while the neutral solar wind and perhaps the HSTOF data favor a component at higher energies which can penetrate well inside of 1 AU. This implies that should this secondary stream exist, it likely contains a wide range of neutral speeds, that is, it is very hot.

A natural question is what would cause such a stream and the answer is unclear at best, although there are a couple other relevant issues that should be mentioned. First, it is interesting to note that the apparent direction of the interstellar dust flow is shifted about 10° later in ecliptic longitude than the direction of the interstellar neutral flow [Grün, 2000], although they are consistent to within a 1σ uncertainty. The dust distribution, however, is sufficiently broad so that it is also consistent with a wide range of flow directions. Because dust can serve as a source of neutrals for charge exchange [Banks, 1971], there may be some relationship between the interstellar dust flow and this possible secondary stream.

Second, if the heliosphere is tilted due to the inclination of an interstellar magnetic field, as suggested by some simulations [Ratkiewicz et al., 1998] and illustrated in Figure 6, then perhaps the shift in the data sets presented here is the result of this asymmetry.

Third, Lallement [private communication] has pointed out that evidence suggests that the heliosphere is extremely close to the boundary of the local interstellar cloud in the approximate direction of the Galactic

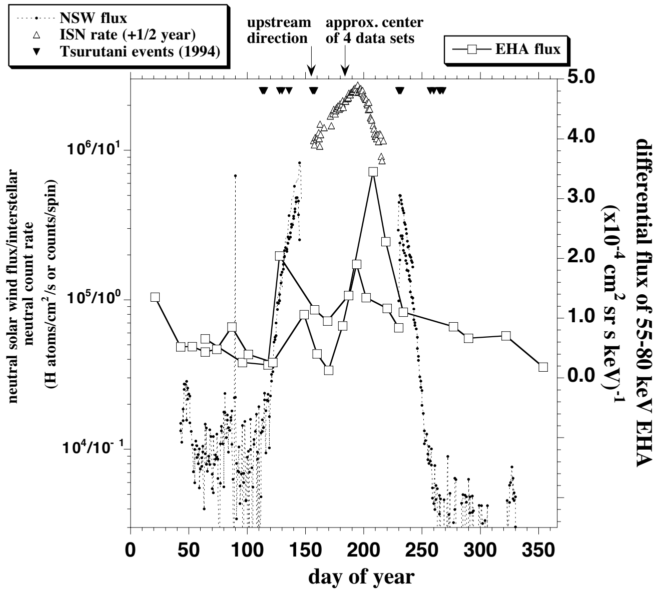


Fig. 5. Four data sets discussed in this paper.

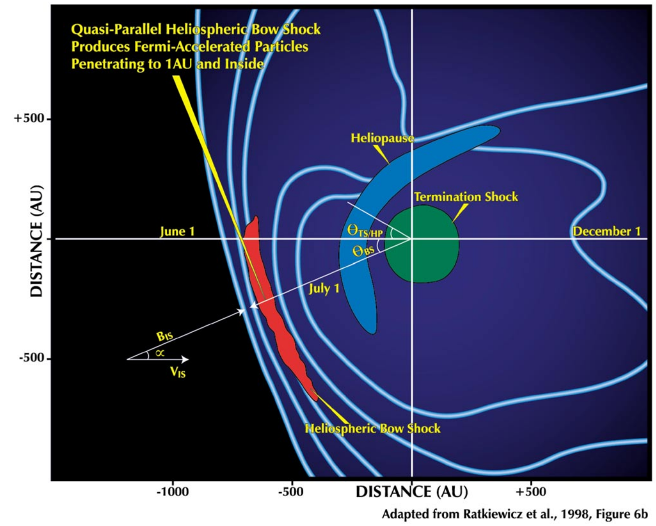


Fig. 6. Angled IS B-field producing heliospheric tilt.

center, albeit with a huge uncertainty [Lallement, 1996; Lallement and Bertin, 1992]. If the next cloud in that direction, the G cloud [Linsky and Wood, 1996], has not already caught up to the LIC [Lallement et al., 1990], between the LIC and the G cloud resides a hot ionized gas of temperature $\sim 10^6$ K, which corresponds to 150 km/s for protons. If the interface with this hot gas is close (we have only upper limits [Redfield and Linsky, 2000]), then, because of charge exchange between hydrogen and protons, hot neutral H with characteristic speeds of about 150 km/s, perhaps higher, will penetrate the heliosphere from the approximate direction of the Galactic center because of our proximity to the interface. In this scenario, energetic neutrals ($>$ 1 keV) may be observed flowing *towards* the Sun when the Earth is between the Sun and the Galactic center.

In summary, multiple data sets point toward the existence of a secondary stream of energetic neutrals penetrating inside of 1 AU from a direction somewhere between 10° and 40° from the nominal upstream direction. It remains to be fully understood, however, how these data fit in with previous measurements of neutral atoms, pickup ions and UV spectra within the heliosphere and whether or not this interpretation is consistent with these observations.

In particular, a closer look at the spatial distribution of pickup ions appears to be warranted, with a shorter averaging window as used, for example, by Möbius et al. [2002]. This treatment appears to reveal evidence of primary and secondary streams during the period of the IMAGE data sets [2000-2001]. However, it must be borne in mind that the spectral form of the pickup ions resultant from a fast and/or warm secondary stream may not have the same form as that which results from cold interstellar neutral photoionization. The spectral form that is a cut-off at two times the solar wind velocity results from pickup of neutrals travelling slowly with respect to the solar wind.

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